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THE SUPERNOVA REMNANT CTB104A : MAGNETIC FIELD STRUCTURE AND INTERACTION WITH THE ENVIRONMENT

Bülent Uyaniker[1], Roland Kothes[1], and Christopher M. Brunt[1,2]

bulent.uyaniker@nrc.ca, roland.kothes@nrc.ca, chris.brunt@nrc.ca

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ABSTRACT

We present new, high resolution 1420 and 408 MHz continuum images and H I and ^{12}CO (J=1−0) spectral line maps of the diffuse supernova remnant CTB104A (G93.7−0.3). Analysis of the complex continuum emission reveals no significant spectral index variations across the remnant. Three prominences around CTB104A are found to be related to the SNR, while one extension to the east is identified as an H II region associated with a background molecular shell. Small scale polarization and rotation measure (RM) structures are turbulent in nature, but we find a well-ordered RM gradient across the remnant, extending from southeast to northwest. This gradient does not agree with the direction of the global Galactic magnetic field, but does agree with a large-scale RM anomaly inferred from rotation measure data by Clegg et al. (1992). We show that the observed morphology of CTB104A is consistent with expansion in a uniform magnetic field, and this is supported by the observed RM distribution. By modeling the RM gradient with a simple compression model we have determined the magnetic field strength within the remnant as $B_0 \approx 2.3\ \mu$G. We have identified signatures of the interaction of CTB104A with the surrounding neutral material, and determined its distance, from the kinematics of the H I structure encompassing the radio emission, as 1.5 kpc. We also observed clear breaks in the H I shell that correspond well to the positions of two of the prominences, indicating regions where hot gas is escaping from the interior of the SNR.

Subject headings: HII regions — ISM: bubbles — ISM: individual (CTB104A) — magnetic fields — polarization — supernova remnants

1. INTRODUCTION

CTB104A (G93.7−0.3) is a diffuse, thick-shelled supernova remnant (SNR) with four "prominences", extending beyond the main body of the shell. Three of the prominences are polarized, as reported by Mantovani et al. (1991). The radio spectrum of CTB104A ($S_\nu \propto \nu^{-0.42}$) is relatively flat, typical of a mature shell-type SNR in the radiative expansion phase.

In broad terms, CTB104A appears as a double limb-brightened shell. The lack of symmetry between the limbs may be indicative of different shock conditions across the remnant and hence a range of effective evolutionary ages. Kesteven & Caswell (1987) interpret CTB104A as a possible barrel-shaped SNR with the shell of the remnant being physically distorted by the interstellar medium and elongated in the direction of the Galactic magnetic field. This is consistent with the observed morphology of CTB104A, but only for a particular choice of magnetic axis. Consequently, good quality polarization measurements can be used to examine this possibility.

Apart from identifying the origin of the shell morphology, a complete understanding of CTB104A depends upon gaining information on the nature of the prominences extending from the shell. With the exception of the prominence to the east (higher longitude) the prominences do not terminate at a sharp boundary, but rather appear to fade smoothly into the Galactic background emission. These prominences may be "hot blasts" escaping into regions where the density of the environment is presumably relatively low, as suggested by Landecker et al. (1985). A close examination of the surrounding neutral medium may reveal signatures relating to the origin of the prominences.

To diagnose the dominant processes that shape CTB104A and to gain insight on the prominences extending from the remnant, we have compiled high resolution radio continuum data at 1420 and 408 MHz, polarization measurements at 1420 MHz, H I spectral line data and HIRES processed IRAS images (Cao et al. 1997) from the Canadian Galactic Plane Survey (CGPS), as well as ^{12}CO (J=1−0) emission line data at comparable resolution from the Five College Radio Astronomy Observatory (FCRAO). We examine the spectral index distribution with TT-plot analysis between 408 and 1420 MHz for signs of differing shock conditions over the remnant's shell and also towards the prominences. Linear polarization measurements are used to study the overall role of the magnetic field on the expansion of the SNR and to search for spatially variable polarization that is indicative of regions of turbulence and material heated by localized shock compression. We identify signatures of the interaction of the SNR with its surroundings from the CGPS H I line data and use this additionally to constrain the distance to CTB104A as ∼ 1.5 kpc. Finally, we use the FCRAO CO data and HIRES IRAS data to identify one of the prominences as a background H II region, located in the Perseus Arm, and thus not associated with the SNR.

[1] National Research Council, Herzberg Institute of Astrophysics, Dominion Radio Astrophysical Observatory, P.O. Box 248, Penticton, B.C., V2A 6K3 Canada

[2] Department of Physics and Astronomy, The University of Calgary, 2500 University Dr. NW, Calgary, AB, T2N 1N4 Canada

2. OBSERVATIONS

2.1. *CGPS data*

CTB104A was observed at 1420 and 408 MHz in continuum mode, including the Stokes Q, U and V parameters at 1420 MHz. Radio continuum and H I line observations were carried out simultaneously with the Dominion Radio Astrophysical Observatory (DRAO) synthesis telescope (Landecker et al. 2000) as part of the CGPS. HIRES-processed IRAS data (Cao et al. 1997) were also obtained from the CGPS data archive. The CGPS is described by Taylor et al. (2001) and a more detailed description of the data processing routines can be found in Willis (1999). The angular resolution of the DRAO synthesis data varies slightly across the final maps as $1' \times 1'$ cosec$(\delta)(1420/\nu(\mathrm{GHz}))$. Single antenna data are incorporated into the synthesis maps to assure accurate representation of all structures up to the largest scales. The low spatial frequency continuum data are obtained from the Effelsberg Survey at 1420 MHz (Reich et al. 1997) and at 408 MHz from Haslam et al. (1982). The low spatial frequency H I data are from the Low Resolution DRAO Survey of the CGPS region observed with the DRAO 26-m Telescope (Higgs & Tapping 2000).

2.2. *FCRAO CO data*

We have obtained spectral line images of ^{12}CO (J=1−0) emission in the area around CTB104A from the FCRAO 14m telescope. Our mapped area covers Galactic longitudes $\ell \sim 93°$ to $\ell \sim 94.°9$ and Galactic latitudes $b \sim -1°$ to $b \sim +0.°33$, with a somewhat irregular boundary. The CO data for $\ell < 94.°5$ were obtained by Routledge and Moriarty-Schieven (unpublished) in November-December 1994 using the QUARRY 15 pixel focal plane array (Erickson et al. 1992); to this we have added more data at $\ell > 94.°5$, taken during March/April 2001, using the SEQUOIA 16 pixel focal plane array (Erickson et al. 1999). Pointing measurements were carried out using Venus (1994 data) and the SiO maser χ Cygni (2001 data). Both sets of CO data were obtained by position-switching.

The 1994 data have 80 MHz (∼190 km s^{-1}) total bandwidth, with the spectrometer centered on $v_{\mathrm{LSR}} = -45$ km s^{-1} and the 2001 data have 40 MHz (∼95 km s^{-1}) total bandwidth centered on $v_{\mathrm{LSR}} = -30$ km s^{-1}. The spatial sampling and velocity resolution (1.21 times the channel spacing) for the 1994 and 2001 data sets respectively were $25''$, 0.98 km s^{-1} and $22''$, 0.25 km s^{-1}. The spatial resolution (beam FWHM) of the data is $45''$. Both data sets were initially calibrated by the chopper wheel method (Kutner & Ulich 1981) and subsequently converted to the radiation temperature (T_R^*) scale by correcting for forward scattering and spillover losses ($\eta_{fss} = 0.7$). Each data set was convolved to $2'$ spatial resolution and 0.98 km s^{-1} velocity resolution prior to combining them on the same $\ell, b, v_{\mathrm{LSR}}$ grid as the H I data. The resulting sensitivity was 0.29 K and 0.08 K (1σ) for the 1994 and 2001 data sets respectively.

2.3. *Morphology of the SNR*

The radio continuum total intensity maps around CTB104A are shown in Figures 1 and 2, at 1420 and 408 MHz respectively. The remnant has a roughly circular shape consisting of three distinct fragments. A circle of $1.°2 \times 1.°2$ centered at $\ell = 93.°7$ and $b = -0.°3$, fitted by eye and shown in Figure 3, delineates this roughly circular shape. The prominences, identified in Figure 3 by arrows, form an irregular boundary to the otherwise circular remnant. The angular size of the SNR, taking all the prominences into account, is about $1.°3 \times 1.°5$. The northern part of the shell has the highest intensity at both 408 and 1420 MHz maps. The prominence extending toward the south of the SNR, where the shell is incomplete, is a good candidate for an example of the "break out" phenomenon observed in mature SNRs (e.g. Cygnus Loop, VRO 42.05.01 and CTA 1). A similar claim could be made for the other prominences if projection effects are considered.

Disregarding the prominences, we examine the idea that the SNR's morphology could be interpreted as due to the expansion of the remnant in a regular magnetic field. In such a model (e.g. van der Laan 1962) no emission in total-intensity along the field direction is expected if the surrounding magnetic field is uniform on a scale larger than the SNR. The positions of the three shell fragments can support this model only for a particular choice of magnetic field axis. This preferred axis, lying ∼ 20 - 40 degrees north of west [3], partitions the remnant into two halves, one consisting of the north and east fragments and the other consisting of the southwest fragment alone. No other choice of magnetic field axis can validate this model. In Section 2.5 we show that the actual magnetic field axis lies at $\sim 30°$ north of west. Thus, expansion in a uniform magnetic field is consistent with the observed morphology of the SNR.

The diffuse filamentary structure with a bright core seen to the south of the SNR is the H II region S124. The distance of S124 based on the distance of the exciting star from spectrometric data is $d = 2.6\pm0.6$ kpc (Felli & Harten 1981, Brand & Blitz 1993), which excludes a physical relationship between S124 and the remnant since CTB104A is at a distance of ∼1.5 kpc (see Section 3).

2.4. *Spectral analysis*

Spectral indices were computed using the conventional TT-plot method by plotting the brightness temperature values of the 408 MHz maps against those at 1420 MHz. The 1420 MHz data are convolved to the resolution of the 408 MHz map. To avoid oversampling in the TT analysis the maps are regridded to $1'$. In order to reveal any variation in the spectral index across the whole SNR, we have selected regions towards distinctly separable parts of the remnant and performed TT-plot analysis on the data extracted from those individual regions. Regions corresponding to the core of S124 and the extragalactic source 4C50.55 were also included in this analysis for a reliability check on our measured indices. Figure 3 shows the selected regions marked on the 1420 MHz image. The regions were selected in a way to avoid unresolved sources, but this was not always possible. Since these sources are most likely extragalactic, we have checked the images for unresolved sources in the highest resolution image (1420 MHz) and

[3] 20 - 40 degrees counter clock wise with respect to the Galactic plane.

we excluded a circular region with a diameter of $4'$ around these sources. Then we plotted brightness temperature values of both maps with respect to each other and fitted the distribution with a straight line. The slope of this line gives the temperature spectral index β, where $T_B \sim \nu^{\beta} = \nu^{\alpha-2}$. We repeated this analysis by changing the independent variable and obtain another value for β. We then adopted the difference of these two values of β as the error in the spectral index. Spectral indices derived this way are not strongly affected by the presence of unknown backgrounds contributing to the emission brightness at each frequency. The presence of uniform backgrounds will modify only the unimportant constant term in the fit, leaving the derived slope unaffected, while varying backgrounds will tend to increase the scatter.

The results of the TT analysis are plotted in Figure 4. The analysis gives $\alpha = -0.1$ for S124, which is typical for an optically thick H II region. We obtain $\alpha = -0.59$ for 4C50.55, in agreement with the value given by Mantovani et al. (1982) obtained from integrated flux densities compiled from the literature between 178 MHz to 10.7 GHz. Spectral indices generally show a relatively flat spectrum for the SNR and within the errors of the measurements we do not find any variations in the spectral index across the remnant, except for the central region (s4), where we observe a steeper spectrum. However, in the central region the surface brightness is very low, giving rise to high uncertainty.

The boxes e1, e2, e3 ,e4 are positioned to sample the spectral index of the prominences (see Fig. 3 and Fig. 5). The general trend is that spectral indices towards the prominences are similar to those seen in the main body of the SNR's shell, albeit with larger errors arising from the weakness of the prominence emission, except for the region e2 which indicates a thermal spectrum. We interpret the spectral index measurements as supporting evidence that three of the prominences indeed are non-thermal and related to the SNR, as suggested by the overall SNR morphology. The region e2, however, seems to be an unrelated source of thermal origin, and indeed this prominence is unpolarized (see Mantovani et al. (1991) and Section 2.5 below). For further evidence of the association of the remaining three prominences to the SNR we must appeal to the polarization measurements discussed below.

The lower-right panel of Figure 4 shows a TT-plot using the region indicated by dotted lines in Figure 3. From this region we derive a global spectral index of the SNR as $\alpha \sim -0.43$. This calculated spectrum is comparable to the value $\alpha = -0.42$ given by Mantovani et al. (1991), but still flatter than the typical value of $\alpha = -0.5$ for an SNR expanding adiabatically. This indicates that the SNR is most likely already in the radiative phase.

2.5. *Polarization characteristics of the SNR*

Noise corrected polarized intensity (PI) maps are calculated as $PI = \sqrt{U^2 + Q^2 - (1.2\ \sigma)^2}$, where $\sigma = 30$ mK T_B is the rms noise in each map. Polarization angle maps have been derived, as $\psi_\lambda = \frac{1}{2}\ \arctan\frac{U}{Q}$, from the four bands of the DRAO telescopes, each of width 7.5 MHz and centered at 1406.65 MHz (band A), 1414.15 MHz (B), 1426.65 MHz (C) and 1434.15 MHz (D). These maps have been used to calculate the rotation measure across the remnant. In Figure 6 we show the polarized intensity and rotation measure maps of CTB104A. We observe polarization from almost all parts of the remnant. A distinct difference between the total intensity and the polarized intensity images is immediately evident: there are more small-scale structures in the polarized intensity image than in the total intensity image. This is the result of high rotation measure differences on small scales within the remnant, which we assign to turbulence and/or localized shock compression.

The northern part of the remnant is particularly affected by depolarization; a distinct region of low polarized intensity can be seen in this area. Below this area, we observe patchy polarization structures. In the polarization image it is also possible to see filamentary regions where PI is zero. Rather than signalling the absence of polarization, these structures are most likely due to beam depolarization, arising from a fluctuating magneto-ionic medium within the beam.

The percent polarization varies from 5 to 20% over the remnant. The extension at the western edge of the SNR is weakly polarized. There is polarization towards all prominences, except the one in the east. Given the measured spectral indices of the prominences (consistent with a non-thermal spectrum and also similar to the indices in the SNR shell) along with their observed polarization, we conclude that with the exception of the eastern one, the prominences are associated with CTB104A.

Towards CTB104A there is smooth detectable total intensity emission, and yet the detected polarization is dominated by small-scale structures. Bandwidth depolarization can not be the cause, because the four individual bands allow us to calculate RM values as high as $\sim$6000 rad m^{-2}. The spatial filtering of the smooth structures beyond the limited scale of the interferometer affects both the total intensity and the polarization channels in the same way. However, polarized intensity is additionally affected by the foreground Faraday rotation on various scales, even if the intrinsic polarization is smooth.

Clegg et al. (1992) observed RMs from 54 extragalactic sources and reported an anomalous RM region, $\gtrsim 1000$ rad m^{-2}, towards $(\ell, b) \simeq (92^\circ, 0^\circ)$. The angular extent of this region is coarsely constrained by point source probes to be between 1° and 8°, indicating enhanced RMs behind the Cygnus region. By looking at the RM differences of the double-lobe sources they conclude that RM differences are dominated by small-scale structures. The prevalence of small-scale variability is obvious in Figure 6, but the RM structure also has a systematic component — a gradual variation of the RMs in the direction of south-east to north-west, which is very likely related to the structure seen by Clegg et al. (1992). The direction of maximal gradient in RM lies between 30 ± 10 degrees north of west, although this is not easily seen in a gray scale image.

In order to exhibit this gradient more effectively we project the RM distribution on to an axis 30° north of west and show the resulting variation of RM along this axis in Figure 7. The RM measurements show a systematic increase from negative to positive with respect to the position along this axis. We identify this 30° axis as the magnetic field axis in the remnant. The observed orientation of the magnetic field axis supports the idea that the shell configuration in CTB104A arises from expansion in a uniform magnetic field. Indeed, this axis, within the precision to which it can be ascertained, is the only one that can validate this model for CTB104A. The RM gradient indicates that the magnetic field is tangential across the remnant, which is an accepted field configuration for relatively old SNRs.

This RM variation can not be attributed to a foreground Faraday screen, since the required mean electron density would be $\sim$0.2 cm^{-3} (for an assumed magnetic field strength of 1 μG over a pathlength of 1.5 kpc) which is extremely high by typical Galactic standards and should be observable in emission. Further, a local structure capable of producing the RM variation would have to have the exact shape and location as CTB104A, which is unlikely. This magnetic structure is thus intrinsic to CTB104A or to its vicinity.

3. NEUTRAL MATERIAL NEAR CTB104A

To search for signatures of interaction of CTB104A with the surrounding neutral material we now examine the CGPS H I data. The final H I mosaic consists of 9 CGPS fields, which we have convolved to $2'$ resolution. We have integrated the maps at 2 km s^{-1} intervals and have removed the large scale background emission from each channel using the BGF algorithm by Sofue & Reich (1979). These maps are plotted in Figures 8 and 9.

Starting from negative velocities we see emission surrounding the remnant, but the most important concentration of H I is around -2 to -10 km s^{-1}, forming a D-shaped structure surrounding the SNR. This structure slowly fades out with increasing negative velocities. The spatial coincidence of the H I with the continuum emission is more prominent between -6 and -8 km s^{-1}.

Between 10 and 8 km s^{-1} there is an irregular patch of H I emission centered on the SNR, which we tentatively interpret as the cap of the H I bubble moving away from us. The approaching cap is not visible, probably due to confusion with material from the local spiral arm.

As a modifier to the overall shell morphology of the neutral material surrounding CTB104A, there are clear breaks in the shell that correspond well to the positions of two of the prominences. Particularly striking is a large break occurring near the location of the northwest prominence at LSR velocities between ~ -14 and -20 km s^{-1}. There is a plume of neutral material (at $\ell \sim 92\overset{\circ}{.}6$, $b \sim 0\overset{\circ}{.}6$) which appears to extend beyond, and along a similar axis to, the prominence seen at 1420 MHz. In this same velocity range, the neutral material is evacuated from, and appears to encompass, the region into which the southern prominence extends. Towards the remaining, smaller, northeastern prominence associated with the SNR we see no clear signs of interaction with the surrounding neutral material. However, at the location of this prominence, the upper radio shell is broken in two; this suggests that there is a similar escape phenomenon occurring here, but that the complexity of the H I emission on small scales precludes direct identification of interaction of the SNR with its surroundings. We thus interpret the prominences as hot gas from the interior of the SNR escaping into less dense regions, as suggested by Landecker et al. (1985).

We identify the surrounding H I structure at ~ -6 km s^{-1} as defining the rest velocity (relative to the LSR) of CTB104A, which places the remnant at a distance of $\sim 1.5 \pm 0.2$ kpc, assuming a standard flat Galactic rotation curve ($R_\odot$ = 8.5 kpc, $V_\odot$ = 220 km s^{-1}). At this distance the linear size of the remnant is $\sim$35 pc. Note that, at lower negative velocities the structure surrounding the northern part of the SNR is more prominent while the southern part is best visible at higher negative velocities. This indicates that the northern part of the bubble is moving away from us while the southern part is approaching us. Additionally, the radial velocity of the cap at $\sim$10 km s^{-1} indicates an expansion velocity of about 16 km s^{-1} for the bubble.

We also examined our CO-data for a possible correlation with the SNR. But we could not find any structure which might be related. Further observations of the surroundings and the interior of the SNR are necessary, since our measurements only covered the shell of the SNR and the eastern H II region.

4. THE DETECTED H II REGION G94.48-0.3

Towards $\ell = 94\overset{\circ}{.}48$ and $b = 0\overset{\circ}{.}3$ one of the prominences is visible in both 408 and 1420 MHz images. In contrast to the other three structures, we observe no polarization towards this extension of the remnant. Due to the low intensity values and flat spectral index of the SNR, it is not possible to determine whether this prominence is thermal or non-thermal. However, examination of infrared data shows that this structure is seen as a prominent half-shell in 60 μm IRAS emission (see Figure 10). This shell is also identified in our CO line data. We have integrated the CO emission over the velocity interval -55 km s^{-1} to -35 km s^{-1}, over which the CO morphology is similar to that of the shell seen at 60 μm (see Fig. 10). The coincidence of molecular emission, infrared emission and radio emission with a broadly thermal spectrum strongly suggests that the shell is an H II region. Moreover, the observed LSR velocity of the CO emission indicates that the shell has a distance of $\sim$4 kpc. Therefore this previously unknown H II region is located behind the supernova remnant, which we expected since the polarization images reveal no additional depolarization of the supernova remnant in the direction of the H II region.

5. DISCUSSION

CTB104A is striking due to its shape, but more importantly due to its distinct rotation measure gradient. Such a gradient of RM, with a clear symmetry on both sides of the SNR, signifies a tangential magnetic field distribution in the remnant. The shock of the explosion compresses and deforms the magnetic field and thus the remnant carries the signature of the local magnetic field. In order to interpret this RM gradient in terms of the expansion of the SNR in a uniform magnetic field, we need to have information about the large scale magnetic field structure towards the SNR. The current method to determine the direction of the magnetic field in the Galaxy is the use of pulsar rotation measures (see Han et al. 1999), because they are relatively easy to measure and in most cases distances of the pulsars are known. A plot showing the magnetic field direction with respect to the spiral arms of the Galaxy is given in Figure 11. According to this figure, the direction of the ambient magnetic field is pointing away from us and directed towards lower longitudes.

Assuming CTB104A is expanding in this uniform large-scale magnetic field configuration, it should form a bubble by stretching the magnetic field lines as outlined in Figure 12. Such a magnetic bubble would result in a decreasing RM with respect to Galactic longitude (left panel in Figure 12). However the observed RM gradient decreases in the opposite direction, namely, the RM is increasing with longitude. This implies an ambient magnetic field direction opposite to the overall Galactic magnetic field. Thus the orientation of the magnetic field in this region is not parallel to the galactic plane, nor in agreement with the "large-scale" Galactic field, but is consistent with the RM anomaly observed by Clegg et al. (1992). The overall size of this region is not well constrained by the patchy point-source coverage, but it is at least as big as CTB104A and may be as large as ~ 8 degrees; such a large scale feature must be taken into account when modeling the electron distribution of the Galaxy.

We can make use of the observed variation of the RM to estimate the electron density and the magnetic field strength in the shell of the SNR. Based on the flat spectrum, we can assume that the SNR has already entered the radiative phase. Woltjer (1972) defined the beginning of the radiative phase as the time where half of the explosion energy is lost by radiation. The radius $R_{\rm rad}$ of the SNR at this time depends on its explosion energy E_0 and the ambient density n_0 before explosion:

$$R_{\rm rad} = 23.1\ E_0^{5/17}\ n_0^{-7/17}. \tag{1}$$

Assuming a typical explosion energy of 10^{51} erg, we get a lower limit for the ambient density $n_0 \simeq 2.0$. The compression of the material δ in the shell gives an electron spectrum, for Fermi acceleration, with γ defined by

$$\gamma = 2 - \frac{3\ \delta}{\delta - 1}. \tag{2}$$

The spectral index $\alpha = -0.43$ found in Section 2.4, then gives us a compression ratio of $\delta = 4.8$, which is slightly higher than the expected compression of 4.0 for an adiabatically expanding SNR. This results in a lower limit to the electron density of $n_{\rm e} = 9.6\ {\rm cm}^{-3}$, assuming the material in the shell is fully ionized.

The compression of $\delta = 4.8$ and the linear radius of the SNR $R = 17.5$ pc give the width of the compression zone as 1.3 pc. This corresponds to a shell thickness of only $\sim 3'$, although the total intensity map gives the impression of a thicker shell especially towards the north. It is not surprising that the thin shell is not noticeable in the radio map, because of projection effects. It should be remembered that the remnant has not a perfect circular shape. It is in an advanced stage of evolution and the ambient medium structure is quite inhomogeneous. Thus the expanding shell of the SNR should be locally very thin, even though the radio image does not reveal it.

The rotation measure RM is given by:

$$RM = 0.81\ n_{\rm e}\ B_{\parallel}\ L \tag{3}$$

where $B_{\parallel}$ is the component of the magnetic field parallel to the line of sight and L is the path length through the compression zone along the line of sight. For a spherical geometry, L can be expressed in terms of the impact parameter b as

$$L = \sqrt{R^2 - b^2}\ -\ \sqrt{r^2 - b^2} \tag{4}$$

where r is the inner radius of the compressed region. The tangential magnetic field configuration then leads to

$$B_{\parallel} = B_0\ \frac{b}{(R + r)/2}, \tag{5}$$

where B_0 is the constant magnetic field within the compression zone. Inserting Eqns 4 and 5 into 3 gives

$$RM(b) = 1.62\, n_{\rm e}\, B_0\, \frac{b}{(R + r)} \left(\sqrt{R^2 - b^2}\ -\ \sqrt{r^2 - b^2} \right). \tag{6}$$

The rotation measure gradient at the center of the SNR with respect to the impact parameter, b, would then be

$$\frac{dRM(0)}{db} = 1.62\ n_{\rm e}\ B_0\ \frac{1 - r/R}{1 + r/R}. \tag{7}$$

The observed RM distribution, as displayed in Figure 7, indicates that the gradient over the inner part of the remnant is almost constant. We therefore can extract the gradient given in Eqn 7 by fitting a straight line to the RM distribution. The resultant fit gives a slope of 1.30 ± 0.06, also plotted in Figure 7. Thus using the compression factor $\delta = 4.8$, corresponding to $r/R = 0.93$, and the lower limit for the electron density $n_{\rm e} = 9.6\ {\rm cm}^{-3}$ obtained above, we calculate the constant magnetic field in the compressed region as $B_0 \approx 2.3\ \mu$G. This would imply an ambient magnetic field strength of about 0.5 μG.

6. SUMMARY

We have presented new, high resolution H I and continuum images of CTB104A at 408 and 1420 MHz, augmented by CO spectral line maps and HIRES IRAS data at 60μm. Despite the superficial complexity of CTB104A, a simple physical interpretation of the dominant processes at work in the SNR emerges from the CGPS data. We identify the orientation of the local magnetic field, the physical origin of the shell emission and the overall morphology of the surrounding neutral shell that encloses the SNR. The remnant as a whole is indeed complex, however, as revealed by the signatures of localized interaction between the remnant and the surrounding neutral medium.

Polarization and rotation measure structures are dominated by small scale variations, induced by turbulence within the remnant. However, there is a distinct, ordered, rotation measure gradient from negative values in the southeast to positive ones in the northwest. The direction of the rotation measure gradient defines the axis of the magnetic field around the remnant, lying 30° north of west. This magnetic field is local to the remnant and generally counter to the global magnetic field of the Galaxy in this area. This magnetic field structure lies inside a large RM anomaly inferred from rotation measure data by Clegg et al. (1992). The magnetic field strength within CTB104A is $B_0 \simeq 2.3\ \mu$G.

Non-thermal radio continuum emission arises from two shell edges at the expected locations of compression for this magnetic field configuration. A broken shell of neutral material surrounds the SNR. One of the continuum shell edges, to the northeast, is broken in two. At the location of the break, the smaller of CTB104A's three prominences extends from the shell. We find no obvious disruption, or break, in the surrounding neutral shell at the location of this smaller prominence, probably due both to the smaller size of the prominence and the overall complexity of the surrounding H I emission. Towards the two larger prominences, however, the neutral shell is clearly broken, having been presumably less dense at these points prior to disruption. The morphology of the neutral medium, as traced by H I, is consistent with it being pushed by the escaping ionized material in these regions.

In summary, the three prominences around the remnant reveal that CTB104A is probably the best example of the leakage of blasts of ionized material into a low density environment. One extension to the east is identified as a background H II region associated with a massive molecular shell. CTB104A is a relatively old supernova remnant, as deduced from its global spectral index, expanding isothermally within a uniform magnetic field and inside an associated H I shell. The distance 1.5 kpc inferred from the radial velocity of the H I, $v_{\rm LSR} \simeq -6$ km s^{-1}, translates to a mean linear diameter of ~ 35 pc.

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Fig. 1.— 1420 MHz contour plot (top) and gray scale image of CTB104A with a resolution of $65'' \times 49''$ (EW × NS). Contour levels start from 4.8 K T_B and run in steps of 0.5 K T_B. The diffuse structure with a bright core in the lower left corner is the H II region S124.

Fig. 2.— 408 MHz contour plot (top) and gray scale image of CTB104A with a resolution of $3'.7 \times 2'.8$ (EW × NS). Contour levels start from 45 K T_B and run in steps of 10 K T_B. The diffuse structure with a bright core in the lower left corner is the H II region S124

Fig. 3.— Regions used for the TT-plot analysis are displayed on a gray scale image of the region at 1420 MHz on a grid of 1 arc minute. The circles show the regions around the point sources which were excluded. The box with dotted lines shows the region used for an overall spectral index calculation. The dashed circle,centered at $\ell = 93^\circ.7$ ad $b = -0^\circ.3$, shows the approximate circular part of the remnant and has angular dimensions of $1^\circ.2 \times 1^\circ.2$. The arrows indicate the positions of the prominences extending away from the remnants boundary

Fig. 4.— Results of the TT-plot analysis for the selected regions, numbered from 1 to 6. The spectrum relevant for S 124 and 4C50.55 are given in the lower panel. The lower-right panel shows the spectra of the SNR obtained from the region plotted with dotted lines in Figure 3

Fig. 5.— Results of the TT-plot analysis towards the four extensions of the SNR

Fig. 6.— Polarized intensity image (top) of CTB104A at 1420 MHz with overlaid total intensity contours. Contours start at 7.0 K T_B and run in steps of 0.5 K T_B. Lower panel shows the rotation measure image of the same region. White contour is at -100 rad m^{-2} and black contour is at 100 rad m^{-2}

Fig. 7.— Rotation measure distribution as a function of the angular distance from the center of CTB104A, $(\ell, b) = 93^\circ.7, -0^\circ.3$, projected on to the magnetic field axis, which makes an angle of 30° with respect to the Galactic plane. The straight line is the fit to the RM gradient as explained in the text

Fig. 8.— Neutral hydrogen data at $2'$ resolution integrated over 2 km s^{-1} intervals, between 10 and -6 km s^{-1}. The overlaid contours are from the 1420 MHz continuum image

Fig. 9.— Same as Figure 8 but for the velocity interval -8 to -24 km s^{-1}

Fig. 10.— CO emission over the velocity interval between -55 and -35 km s^{-1} (left) and infrared 60 μm (right) images towards CTB104A. White contours show the total intensity emission at 1420 MHz

Fig. 11.— Direction of the magnetic field with respect to the spiral arms in the Galaxy, obtained from the pulsar rotation measure data, adopted from Han et al. (1999). The approximate position of CTB104A is marked by a cross

Fig. 12.— Plot of the model for an SNR expanding in a regular magnetic field. The magnetic field direction and its parallel component given by the pulsar rotation measure data are shown on the left. Also shown are the stretch of the magnetic field lines due to the SNR expansion and the relative RM strength and direction with respect to the given magnetic field configuration. The sketch on the right shows the same configuration but the direction of the magnetic field is reversed

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